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Volatiles Released during Emplacement of Mare Basalts: Implications for a Lunar Atmosphere

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The Current Lunar Atmosphere

- Detected via Apollo 14, 15 (*e.g.*, *Johnson et al.*, 1972; *Stern*, 1999 and references therein)
  - Night Pressure: ~1.6×10^{-13} atm
  - Day Pressure: ~1.6×10^{-15} atm
  - Ar, CH_4, He, CO, CO_2, N_2, Rn
- Surface Boundary Exosphere with various sources (*Stern*, 1999):
  - Solar Wind Impingement
  - Thermal, Sputtering, Chemical
  - Meteoritic
  - Outgassing of Internal Volatiles

Lunar ALSEP deployed during Apollo 12.

- Enhanced impact and volcanic activity >3 Gyr may have enabled development of more substantial collisional lunar atmosphere.

Finding an Ancient Lunar Atmosphere

1. Lunar Mare Production Function
   - Volume of mare
   - Age of emplacement
2. Volatile Mass Production Function
   - Lunar mare volatile distributions.
3. Atmosphere Pressure, Duration
4. Final Volatile Sink

LROC WAC mosaic

Lunar Mare Volume

- Volume of mare in lunar basins

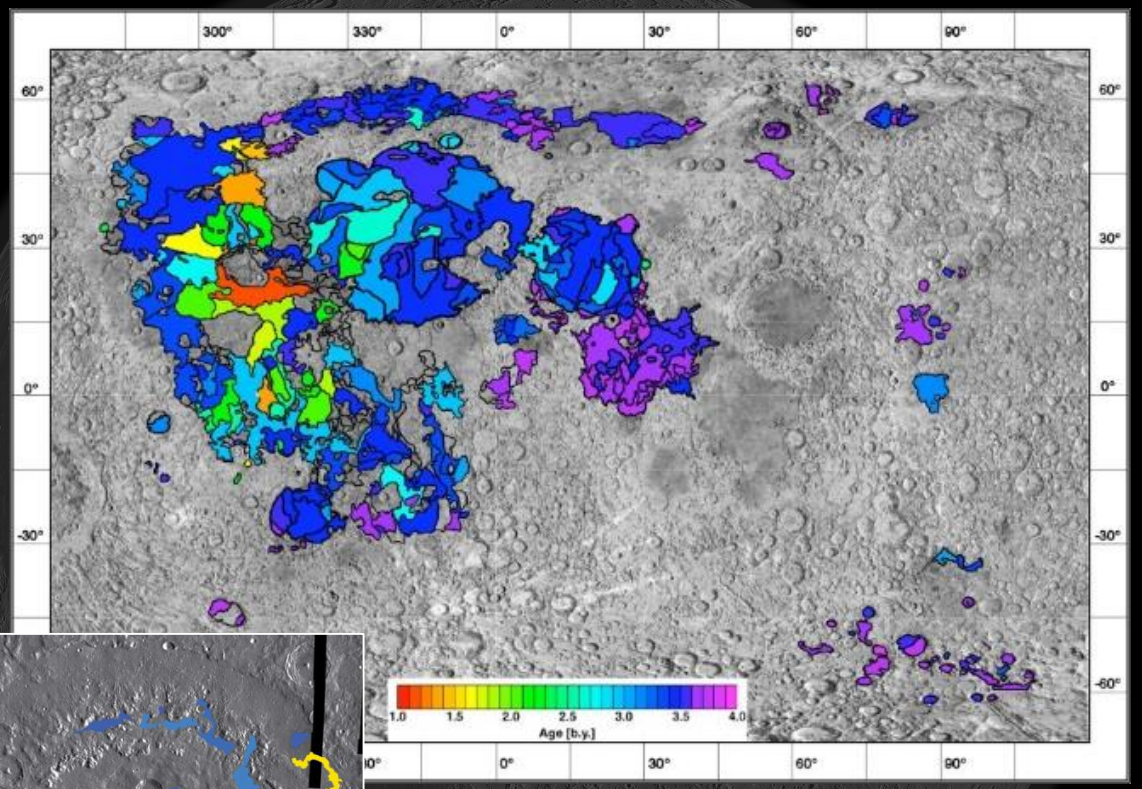
Table 1: Total volume of mare in lunar basins				
Basin	Total Area (km^2)	Ave. Thickness (m)	Volume (km^3)	Thickness Reference
Crisium	156,103	2,940	458,943	Williams and Zuber 1998
Grimaldi	15,359	3,460	53,142	Williams and Zuber 1998
Humorum	101,554	3,610	366,611	Williams and Zuber 1998
Imbrium	1,010,400	5,240	5,294,497	Williams and Zuber 1998
Nectaris	64,277	840	53,993	Williams and Zuber 1998
Orientale	75,975	88	13,294	Whitten et al 2011
Oceanus Procellarum	1,757,799	325	571,285	Hörz 1978
Serenitatis	342,716	4,300	1,473,679	Williams and Zuber 1998
Smythii	28,075	1,280	35,937	Williams and Zuber 1998
South Pole - Aitken	206,430	Varied	153,240	Yingst and Head 1997
Tranquillitatis	371,257	350	129,940	Hörz 1978

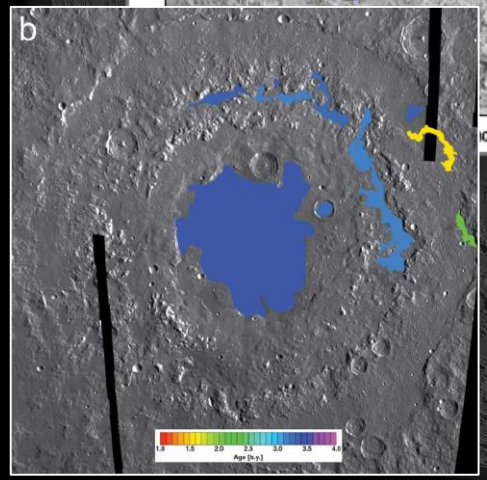
Total volume of mare: ~9×10^6 km^3, similar to previous estimates.

(1×10^7 km^3, Head and Wilson, 1992)

Timing of Mare Emplacement

- Timing of mare emplacement
  - Area, thickness of each mapped unit.
  - Age of each mapped unit from crater counting
  - Remaining mare volume assumed to be emplaced at time of oldest surface unit.

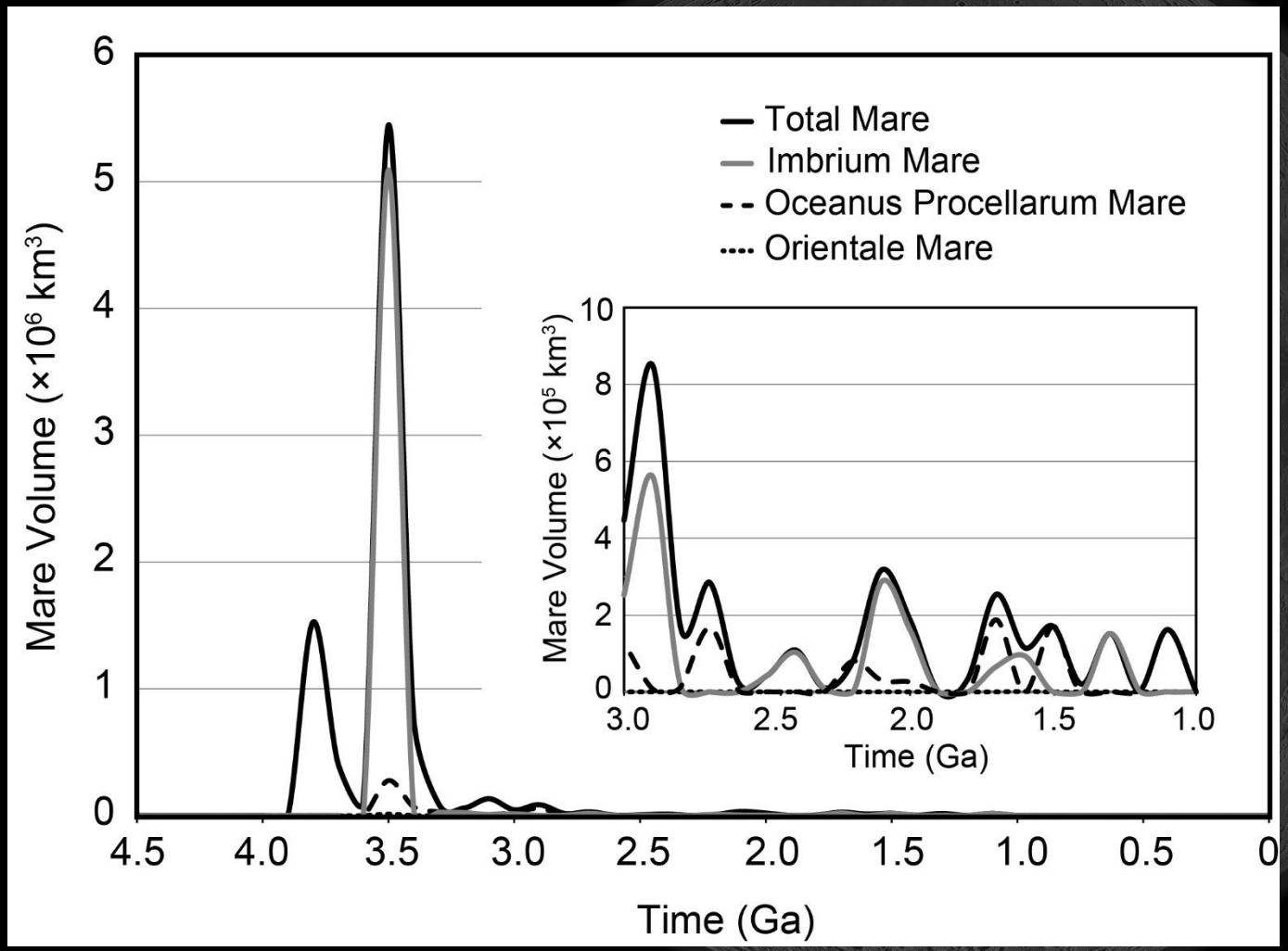




Hiesinger et al., 2011;
Whitten et al., 2011

Lunar Mare Volume over Time

Volume of erupted basalts as a function of time



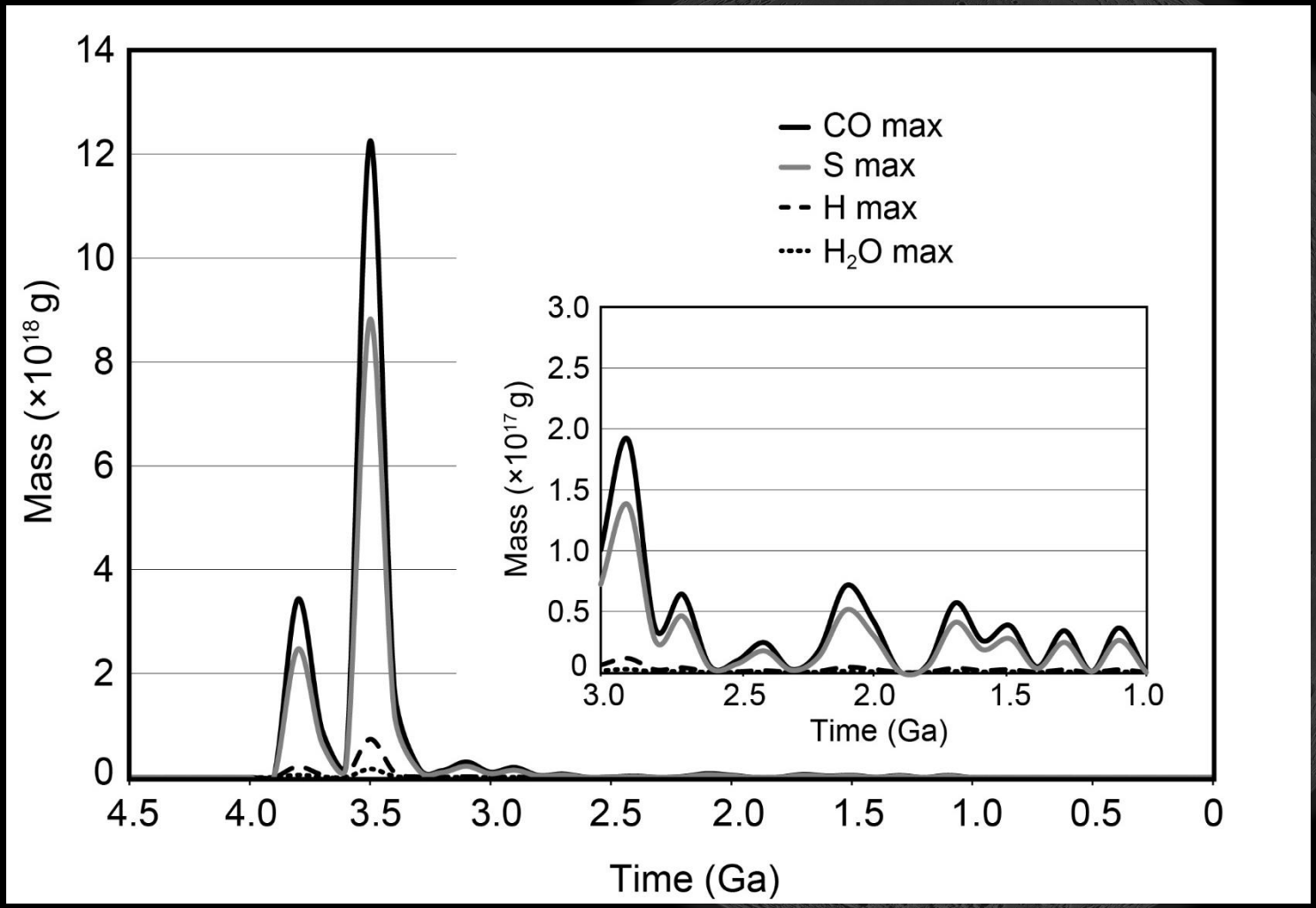
Mass of Released Mare Volatiles

- Assume density of 3000 kg/m^3, calculate total mass of mare.
- Using mare volatile measurements from literature, calculate mass of each released volatile.

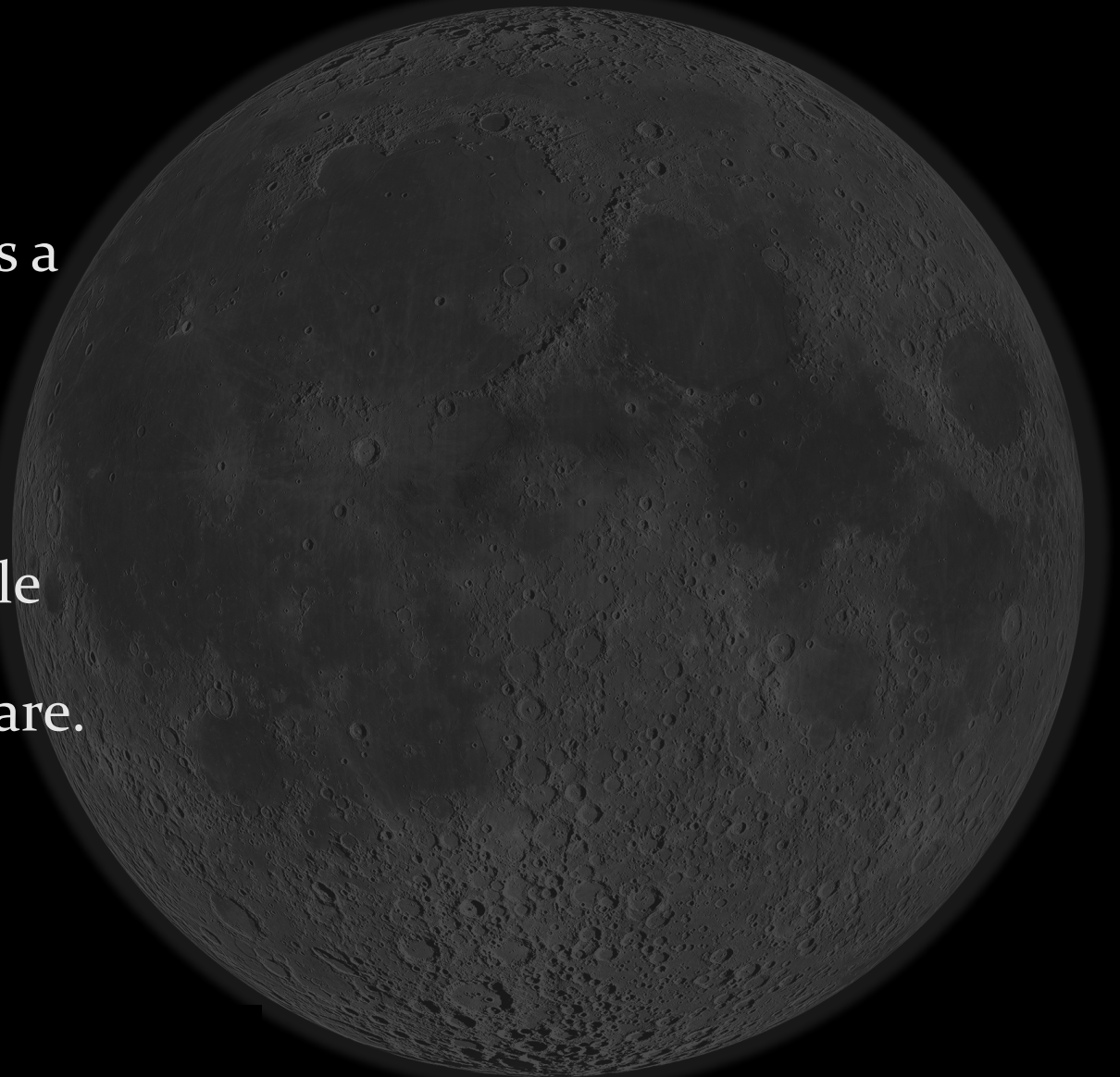
Mare Volatiles	Min (ppm)	Max (ppm)	Released (%)	Min (ppm)	Max (ppm)	
CO	80	750	100	80	750	Sato 1979
H_2O	2	10	90	1.8	9	Robinson and Taylor 2014; Elkins-Tanton and Grove 2011
H	0.007	45	100	0.007	45	McCubbin et al., 2010
S	200	600	90	180	540	Shearer et al., 2006

Mass of Released Mare Volatiles

Volatile mass from all mare eruptions assuming max mare volatile content



Atmospheric Pressure, Duration

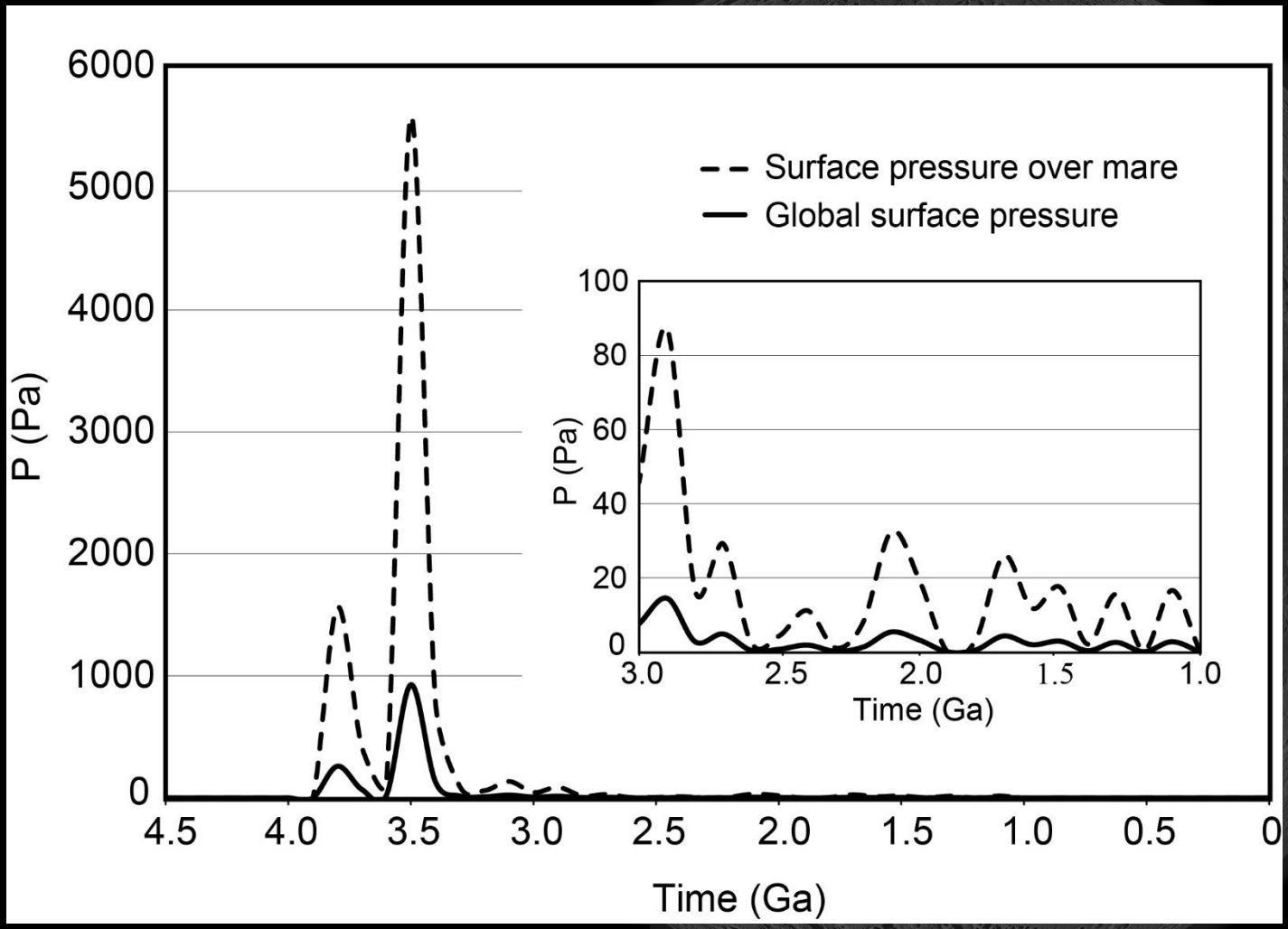


- Total mass released as a function of time.

$$P_{surf} = \frac{mg}{A}$$

- Distributed over whole lunar surface vs. Concentrated over mare.

Atmospheric Pressure, Duration



Implications for a Lunar Atmosphere

- Surface Pressure
  - At peak, ~1000 Pa (~0.01 atm).
    - Global Distribution:
      - ~1% of Earth's current surface pressure.
      - ~1.5 times greater than Mars' current surface pressure.
    - Concentrated Distribution over Mare:
      - ~5,600 Pa (0.06 atm): 6% of Earth's pressure.
- Scale Height of ancient lunar atmosphere: $\frac{KT}{mg}$
  - At Noon: ranges from ~60 km (S) to 1000 km (H_2).
  - At Midnight: ranges from ~15 km (S) to 250 km (H_2).

Implications for a Lunar Atmosphere

- Duration of Lunar Atmosphere
  - Loss rate controlled by particle interactions.
    - Total atmospheric mass exceeds 10^{11} g (*Vondrak*, 1974), -> 10^{4} g s^{-1}
      - Peak volcanic activity (~3.5 Ga), total mass is 10^{16} kg.
        - Source half-width > 500 m -> volatile effusion rate >10^{7} g s^{-1}. (Wilson and Head, 1980)
      - Resulting atmosphere may have required ~70 Ma to dissipate.

- Sink of Lunar Atmospheric Volatiles
  - If 0.1% of vented mare water (~10^{17} g) is trapped in PSRs, volcanically-derived volatiles could account for all water in PSRs (10^{14} g, *Eke et al.*, 2009).